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# CIRCULAR PHOTON DRAG EFFECT IN QUANTUM WELLS



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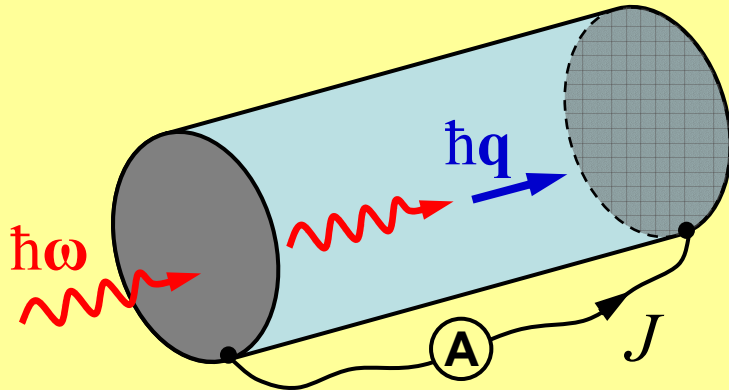
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# CIRCULAR PHOTON DRAG EFFECT IN QWS

## Outline

- Introduction. Photon Drag in semiconductors
- Phenomenological analysis:  
Photogalvanic effect vs. Photon Drag effect
- Experiment. Intersubband transitions in (110)-QWs
  - normal incidence: Circular Photogalvanic effect
  - oblique incidence: Circular Photon Drag
- Microscopic model of the Circular Photon Drag

# PHOTON DRAG OF CHARGE CARRIERS



Photocurrent caused by transfer of photon linear momenta to free carriers

Electric current density

$$j^{\text{Drag}} \propto e\tau_p K(\omega)I$$

$e$  the electron charge

$\tau_p$  the momentum relaxation time

$K(\omega)$  the absorption coefficient

$I$  the light intensity

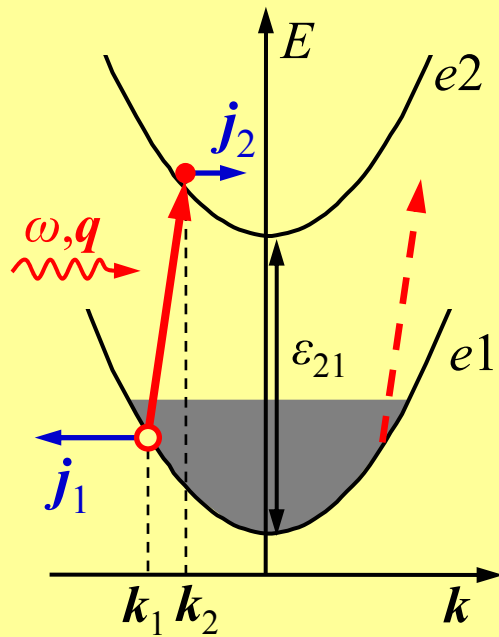
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## First observation: Bulk $p$ -Ge

A.M. Danishevskii et al.,  
Sov. Phys. JETP **31**, 292 (1970)

A.F. Gibson et al.,  
Appl. Phys. Lett. **17**, 75 (1970)

# INTERSUBBAND TRANSITIONS IN N-TYPE QWS



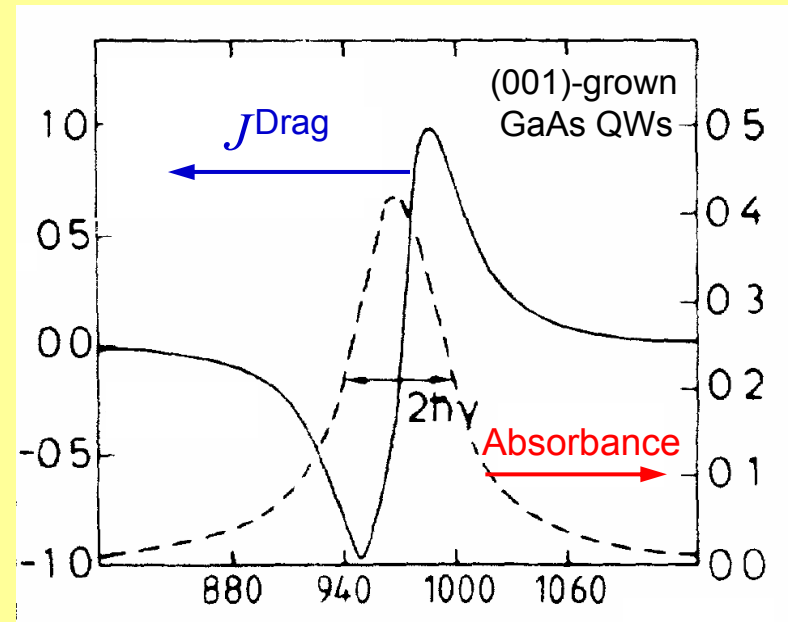
Momentum and energy conservation

$$\mathbf{k}_2 = \mathbf{k}_1 + \mathbf{q}, \quad \varepsilon_{e2, \mathbf{k}_2} = \varepsilon_{e1, \mathbf{k}_1} + \hbar\omega - \varepsilon_{21}$$

Electric current

$$\mathbf{j}^{\text{Drag}} = \mathbf{j}_1 + \mathbf{j}_2 \propto e(\tau_2 \mathbf{k}_2 - \tau_1 \mathbf{k}_1) \eta(\omega) I$$

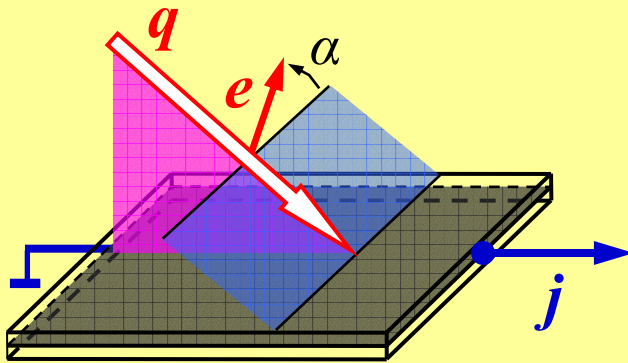
Spectral dependence



S. Luryi, PRL **58**, 2263 (1987)

A.D. Wieck, H. Sigg, K. Ploog,  
PRL **64**, 463 (1990)

# POLARIZATION DEPENDENCE



Selection rules for the intersubband optical transitions

s-polarization ( $\alpha=0$ )  $\rightarrow \eta \neq 0$

p-polarization ( $\alpha=90^\circ$ )  $\rightarrow \eta = 0$

QW absorbance

$$\eta \propto |e_z|^2$$

Polarization dependence of the Photon Drag current

$$j^{\text{Drag}} \propto \eta \propto \sin^2 \alpha$$

This is Linear Photon Drag

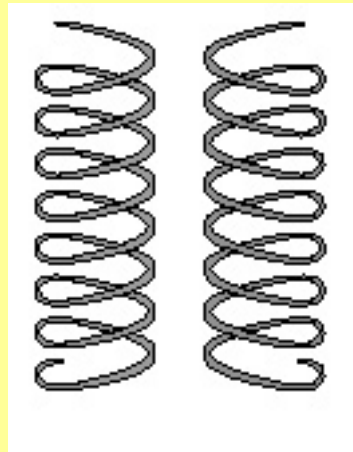
# CIRCULAR PHOTON DRAG ?

Does a Helicity-Dependent Photon Drag contribution exist?



$\sigma^+$

$\sigma^-$



# PHENOMENOLOGICAL DESCRIPTION

Electric current induced by light

$$j_\lambda = I \left\{ \sum_{\mu\nu} \alpha_{\lambda\mu\nu} e_\mu e_\nu^* + \sum_{\mu\nu\delta} \beta_{\lambda\mu\nu\delta} q_\mu e_\nu e_\delta^* \right\}$$

PhotoGalvanic Effect

Photon Drag

$$\sum_{\mu\nu} L_{\lambda\mu\nu} (e_\mu e_\nu^* + e_\nu e_\mu^*) / 2$$

Linear PGE

$$\sum_{\mu\nu\delta} T_{\lambda\mu\nu\delta} q_\mu (e_\nu e_\delta^* + e_\delta e_\nu^*) / 2$$

Linear Photon Drag

$$\sum_{\mu\nu\delta} C_{\lambda\mu} i[\mathbf{e} \times \mathbf{e}^*]_\mu \propto P_{circ}$$

Circular PGE

$$\sum_{\mu\nu} D_{\lambda\mu\nu} q_\mu i[\mathbf{e} \times \mathbf{e}^*]_\nu \propto P_{circ}$$

Circular Photon Drag

$I$  the light intensity,  $\mathbf{q}$  the photon wavevector,  
 $\mathbf{e}$  the (unit) light polarization vector,

E.L. Ivchenko & G.E. Pikus, 1980

# SYMMETRY ANALYSIS

- ✓ Bulk zinc-blende-type compounds (GaAs etc.)

Circular PGE:  $C_{\lambda\mu} = 0$ , Circular Photon Drag:  $D_{\lambda\mu\nu} = 0$

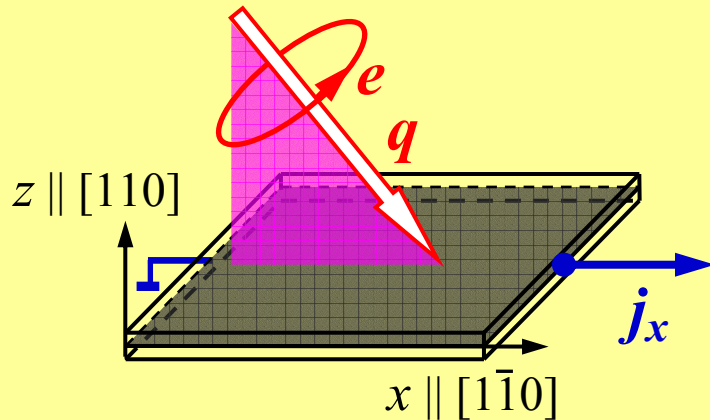
Helicity-dependent photocurrents are forbidden

- ✓ Low-dimensional zinc-blende-type structures

Both Circular PGE and Circular Photon Drag are allowed



# ASYMMETRICAL (110)-GROWN QUANTUM WELLS



$C_s$  point-group symmetry

Helicity-dependent photocurrent

$$j_x \propto \left( C [\mathbf{e} \times \mathbf{e}^*]_z + D q_x i [\mathbf{e} \times \mathbf{e}^*]_x \right) I$$

$$\propto P_{circ} \qquad \qquad \qquad \propto P_{circ}$$

Circular PGE

Circular  
Photon Drag  $\propto q_x$

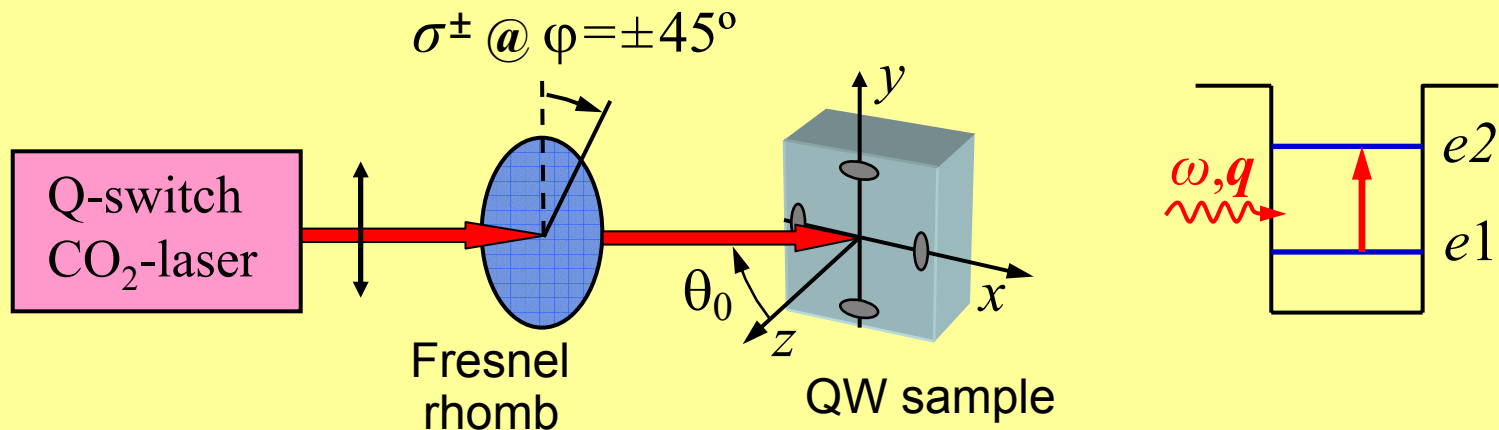
$\mathbf{e}$  the polarization vector  
 $\mathbf{q}$  the photon wavevector  
 $I$  the light intensity
 } inside the sample

# EXPERIMENT: SAMPLES AND TECHNIQUE

**Samples:** (110)-grown *n*-type GaAs/AlGaAs QWs

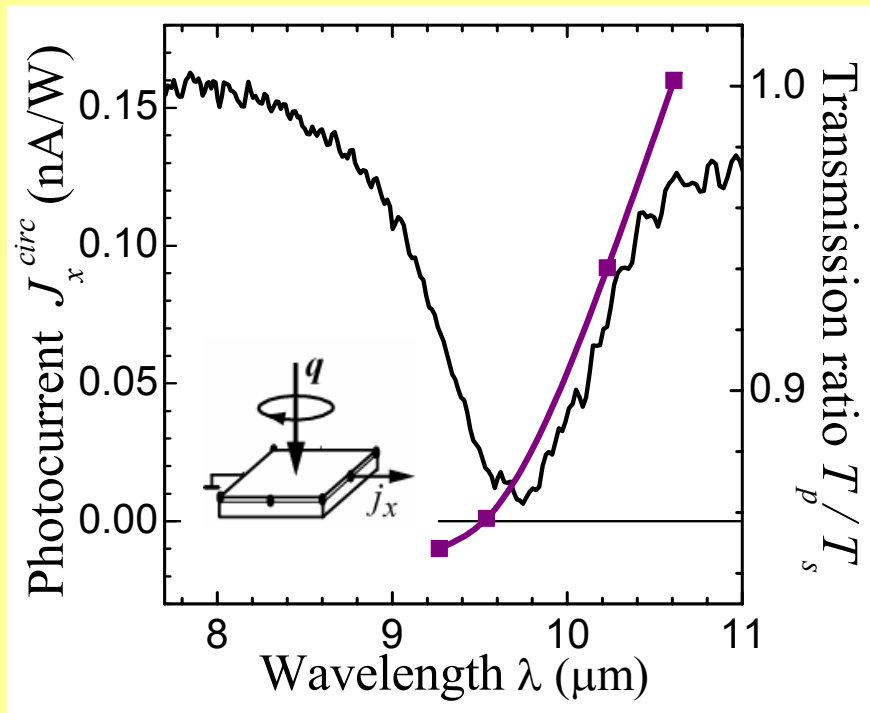
- QW width = 8.2 nm
  - Barrier width = 40 nm
  - Si-doped layers (10 nm) in barriers
  - Electron density =  $7 \cdot 10^{11} \text{ cm}^{-2}$  per QW
- } 100 periods

## Experimental technique

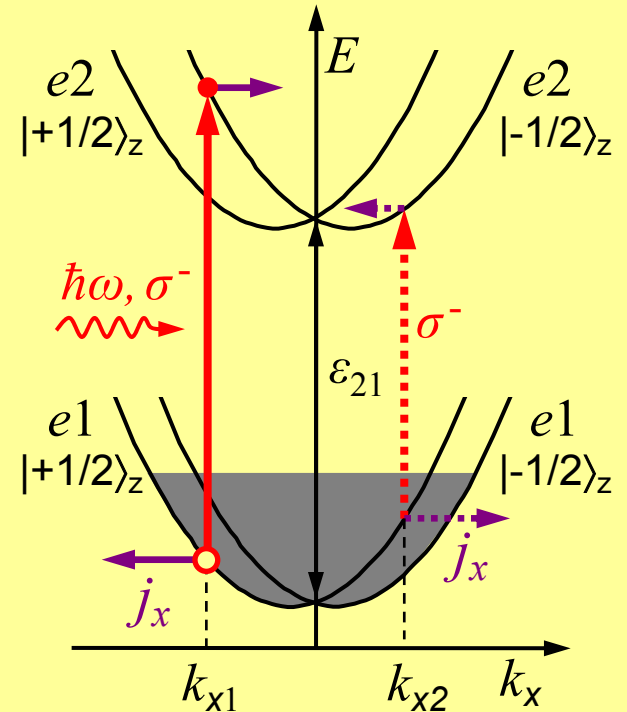


Circular photocurrent  $J^{circ} = [J(\sigma^+) - J(\sigma^-)] / 2$

# EXPERIMENT: NORMAL INCIDENCE



## Mechanism of Circular PGE



Circular Photocurrent

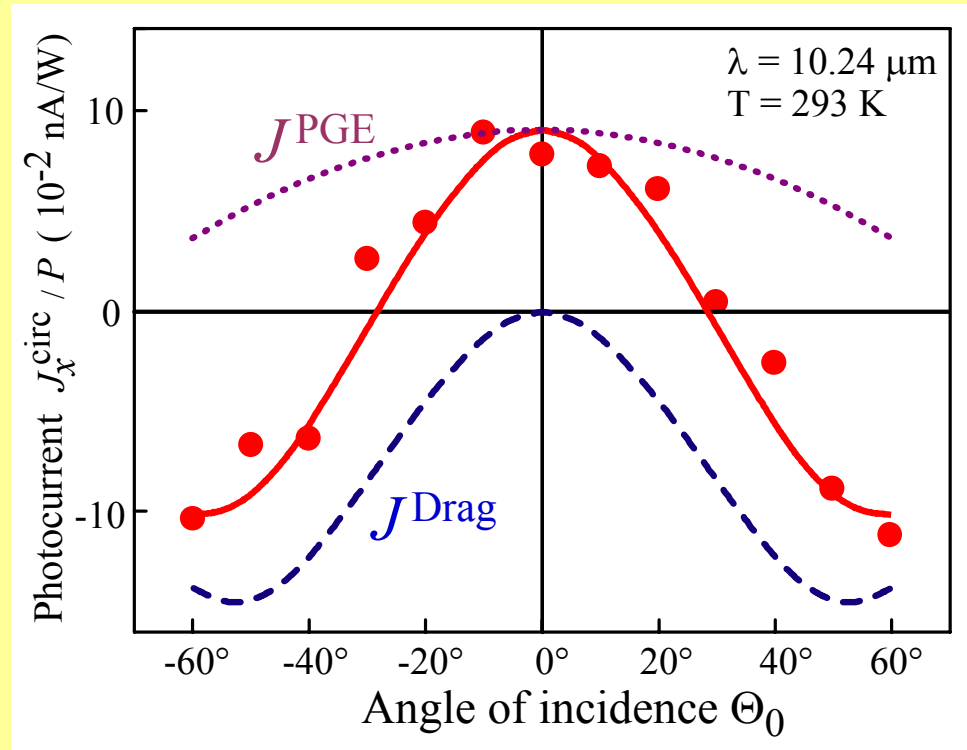
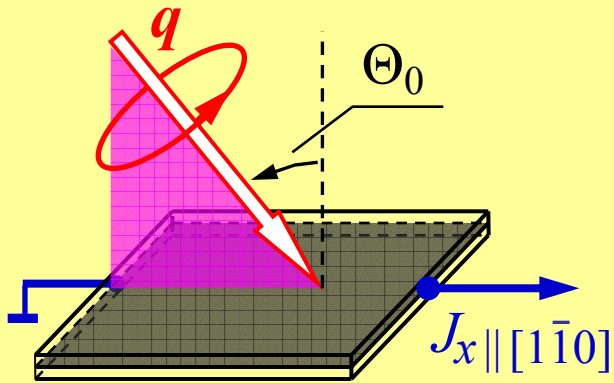
$$j_x \propto t_p t_s \left( C[\mathbf{e} \times \mathbf{e}^*]_z + D q_x i[\mathbf{e} \times \mathbf{e}^*]_x \right) I$$

Circular PGE

- spin-orbit splitting
- spin-sensitive transitions

PRB **68**, 035319 (2003)

# EXPERIMENT: OBLIQUE INCIDENCE



## Circular Photocurrent

$$j_x \propto t_p t_s \left( C [\mathbf{e} \times \mathbf{e}^*]_z + D q_x i [\mathbf{e} \times \mathbf{e}^*]_x \right) I$$

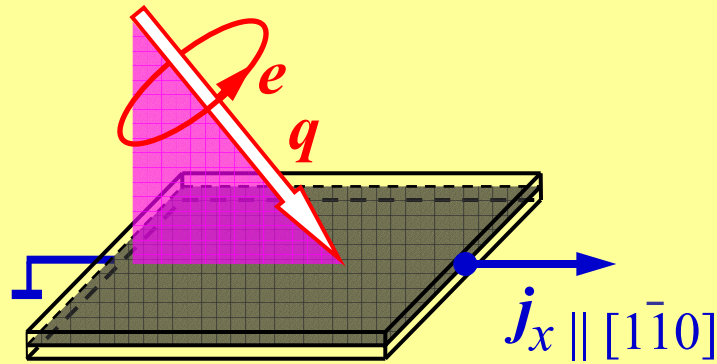
$$\propto \cos \Theta_0$$

Circular PGE

$$\propto q \sin^2 \Theta_0$$

Circular Photon Drag

# MICROSCOPIC MODEL OF CIRCULAR PHOTON DRAG



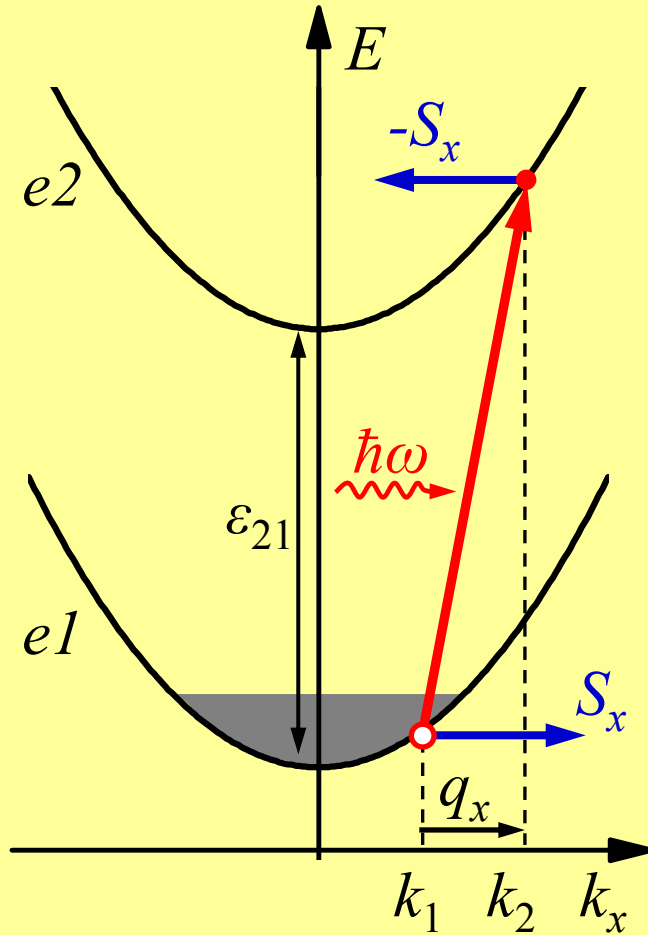
Photocurrent

$$j_x \propto q_x i[\mathbf{e} \times \mathbf{e}^*]_x I \propto q_x P_{circ} I$$

Three-stage process:

- I. Helicity ( $P_{circ}$ ) and wavevector ( $q$ ) dependent optical orientation
- II. Spin rotation in an effective magnetic field
- III. Electric current caused by asymmetry of spin relaxation

# I. OPTICAL ORIENTATION OF ELECTRON SPINS



Energy and momentum conservation

$$\varepsilon_{e2,k2} = \varepsilon_{e1,k1} + \hbar\omega - \varepsilon_{21}$$

$$k_2 = k_1 + q_x$$

Spin-dependent selection rules  
for  $\sigma+$  circularly polarized light

$|e1, -1/2_x\rangle \rightarrow |e2, -1/2_x\rangle$  high rate

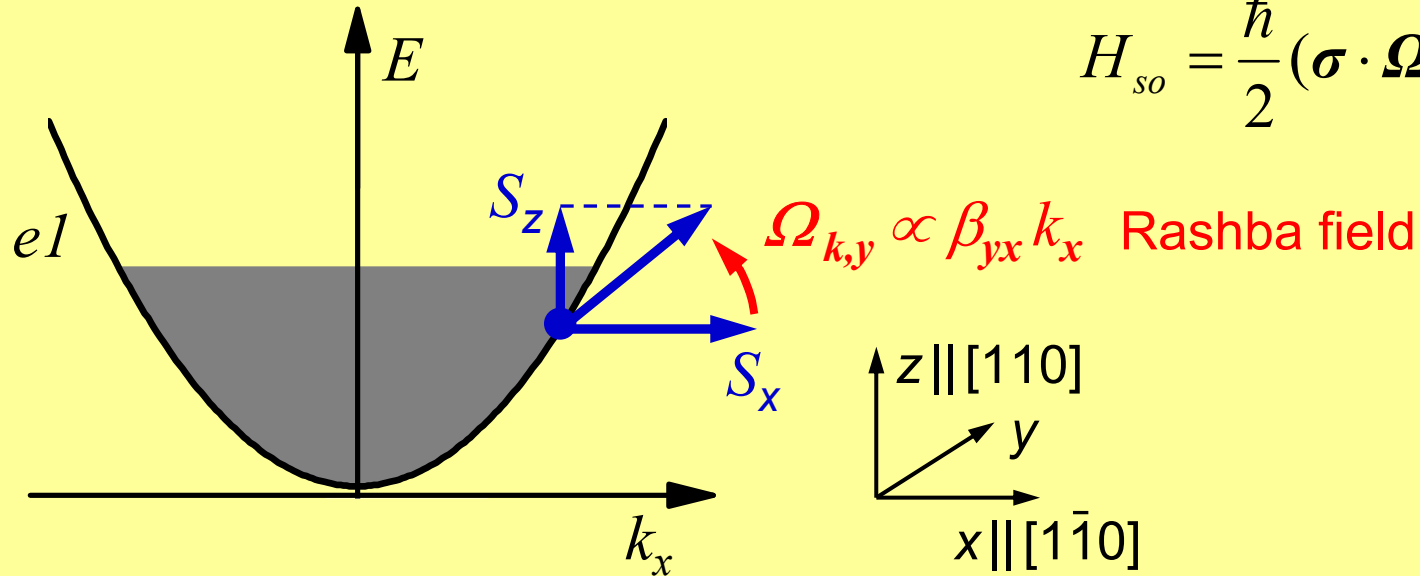
$|e1, +1/2_x\rangle \rightarrow |e2, +1/2_x\rangle$  low rate

JETP **99**, 379 (2004)

## II. SPIN ROTATION IN EFFECTIVE MAGNETIC FIELD

Effective magnetic field  
caused by spin-orbit coupling

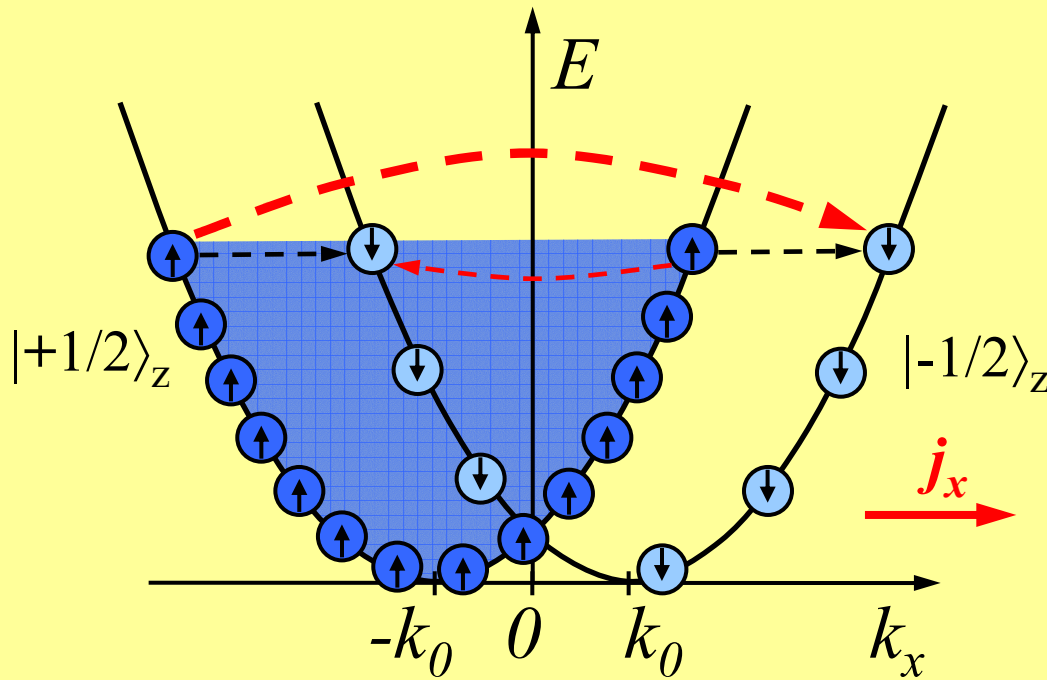
$$H_{so} = \frac{\hbar}{2} (\boldsymbol{\sigma} \cdot \boldsymbol{\Omega}_k)$$



Generation of the spin component  $S_z$

$$\dot{S}_z = \Omega_{k,y} \tau_p \dot{S}_x \propto q_x P_{circ} I$$

### III. SPIN-GALVANIC EFFECT



Asymmetry of spin relaxation processes

Conversion of spin  
into electric current

$$\mathbf{S} \rightarrow \mathbf{j}$$

(110)-grown QWs

$$S_z \rightarrow j_x$$

$$S_x \not\rightarrow j_x$$

Electric current

$$j_x \propto S_z \propto q_x P_{circ} I$$

Nature **417**, 153 (2002)



# CIRCULAR PHOTON DRAG EFFECT IN QWS

## Summary

- ✓ Circular Photon Drag has been observed in QW structures
- ✓ Experimental results are well described by the developed phenomenological theory
- ✓ Microscopic model of the Circular Photon Drag is proposed. It is a three-stage process that involves
  - light wavevector and helicity dependent optical orientation
  - spin rotation in an effective magnetic field
  - spin-galvanic effect caused by spin-relaxation asymmetry